Laterally-doped heterostructures for III-N lasing devices

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Abstract

To achieve a high-density electron-hole plasma in group-III nitrides for efficient light emission, we propose a planar two-dimensional (2D) $p-i-n$ structure that can be created in selectively-doped superlattices and quantum wells. The 2D $p-i-n$ structure is formed in the quantum well layers due to efficient activation of donors and acceptors in the laterally doped barriers. We show that strongly non-equilibrium 2D electron-hole plasma with density above $10^{12}\,cm^{-2}$ can be realized in the $i-$region of the laterally biased $p-i-n$ structure, enabling the formation of interband population inversion and stimulated emission from such a LAteral Current pumped Emitter (LACE). We suggest that implementation of the lateral $p-i-n$ structures provides an efficient way of utilizing potential-profile-enhanced doping of superlattices and quantum wells for electric pumping of nitride-based lasers.

Currently AlGaN and InAlGaN based heterostructures are of great interest for short-wavelength optoelectronic devices, i.e., light-emitting diodes (LEDs), laser diodes (LDs) and photodetectors, operating with radiation that covers the spectral range from green to deep-ultraviolet.[1−3] Development of light emitting devices in this spectral range is stimulated by a number of practically important tasks including highly-efficient lighting, high-density optical storage, stimulation of chemical processes, bio-medical applications, etc. Pumped by the electrical current, blue LDs and green-, blue-LEDs have been realized in InGaN/InAlN structures and are commercially available.[4] Efficient UV electroluminescence of AlGaN has also been observed recently.[5]

Further improvement in the performance of group-III nitride based optoelectronics requires solution of an important problem - obtaining high-density hole currents in bipolar structures. It is well established that the difficulties in achieving high hole concentrations mostly come from the deep energy levels of known acceptors.[2,3,6,7]

It has been shown[6,8,9] that in a p-doped superlattice (SL) the average hole concentration can be considerably enhanced due to high activation efficiency of in-barrier acceptors that supply the holes into quantum wells (QWs). The holes, however, are mostly confined inside the QWs where their concentrations can exceed $10^{13}\,cm^{-2}$.[9] The potential barriers that separate the QWs can be as high as 100 meV to 400 meV. These barriers hinder participation of the holes in *the vertical transport* typical for standard light-emitting devices. In this Letter, we propose to utilize *the lateral transport* of holes and electrons confined in group-III nitride QWs and SLs for high-intensity light emission.[10]

The main element of the proposed structures is a single QW schematically illustrated in Fig. 1. The QW layer is confined by selectively-doped barriers. Each barrier is doped laterally, so that an initial region doped with acceptors is followed by an undoped (intrinsic) region and, finally, by the region doped with donors. Thermal activation of the dopants in the barrier supplies carriers into the QW layer. Since the nitrides form type-I heterostructures, the QW layer accumulates both types of free carriers which lead to the formation of lateral $p-i-n$ structure. Such $p-i-n$ structures can be fabricated by using re-growth techniques,

position-dependent implantation methods,[11] etc. The contacts are to be made to p and n regions as shown in the Fig. 1(a).

The energy band diagram corresponding to an unbiased lateral $p-i-n$ structure is shown in Fig. 1(b). The energy barriers separating p, i, and n regions arise due to the formation of charged regions. Although the band bending is similar to that of a $p-i-n$ homostructure, the charge regions in a multilayered system are formed differently. Indeed, for a $p-i-n$ homostructure the *local* charge neutrality takes place in the p and n regions and the uniformly charged (depletion) layers arise at the $p-i$ and $i-n$ junctions. In the planar multilayered structure, the barrier and QW layers are electrically charged in the doped regions. The quasi-neutrality occurs *on average* for any cross-section far from the junctions. For the cross-sections near the junctions, the average charge is not zero. This charge is responsible for the formation of potential barriers at the junctions. In a forward biased structure, the potential barriers decrease providing for an injection of confined holes and electrons into the i-region. This planar *double injection* gives rise to a non-equilibrium two-dimensional (2D) electron-hole plasma in the i region. Radiative recombination of the plasma in the active region results in stimulated light emission. A SL arranged from QWs considered here will from an efficient souece of radiation - LAteral Current pumped Emitter (LACE).

For the case of vertical transport, the theory of double injection in the $p-i-n$-homostructures and heterostructures is well developed.[12] It is based on a few well proven assumptions: (i) in electrically biased structures, the p, i and n regions are mostly quasi-neutral, and (ii) the charged (depleted) regions remain very narrow. The assumptions allow one to avoid a detailed description of the processes in the depletion regions. To expand this approach to lateral double injection, we need to analyze and compare the length scales characterizing the structure under consideration. These include different groups of the scales: the geometric scales - the QW layer thickness d_{QW}, the barrier layer thickness d_B, and the size of the i region w; the kinetic lengths - diffusion lengths of the electrons L_n, and holes L_p (in general, different for the p, n and i regions); and the lengths of screening of an electric charge

by carriers $l_{sc}^{n,p}$. In light emitting devices the i region should be extended: $w \geq L_n, L_p$, where the macroscopic diffusion lengths are of the order of μm, while the screening lengths l_{sc} are less than 10 nm.[13] Thus, we obtain the following inequalities: $w \geq L_n, L_p \gg d_{QW}, d_B \geq l_{sc}$.

The lateral extensions of $p-i$ and $i-n$ junctions are estimated to be less than, or of the order of, d_{QW}, d_B. Based on the above inequalities, we conclude that the charged layers are very narrow and electron-hole recombination is negligible there. These estimates allow one to study the lateral double injection by the use of the Shockley approach.[12] We can consider the extended i region as quasi-neutral with the carrier transport described by the bipolar drift-diffusion equations. Furthermore, the lateral electric fields inside the p and n regions are expected to be negligible (due to the uniformity along the x direction). In the narrow charged regions, we subject the equations to the relevant boundary conditions.

In narrow QWs, the electrons and holes are quantized and populate the lowest n and p subbands. Then, directing the x axis along the QW, the equations for the bipolar plasma become:

$$\frac{dj_n}{dx} = \frac{dj_p}{dx} = -R\,, \tag{1}$$

$$j_n = -\mu_n nE - D_n\frac{dn}{dx}\,, \quad j_p = \mu_p pE - D_p\frac{dp}{dx}\,, \tag{2}$$

where E is the electric field; n, p are the areal concentrations; j_n, j_p are the flux densities; μ_n, μ_p are the mobilities and D_n, D_p are the diffusion coefficients for the electrons and the holes, respectively; and R is the rate of recombination. We will label these parameters by the upper indices p, i and n for the respective regions. Equations (1) and (2) have the same form for all regions. In the i region, the quasi-neutrality condition yields:

$$E = \frac{J}{e(\mu_p^{(i)} + \mu_n^{(i)})p^i} + \frac{D_p^{(i)} - D_n^{(i)}}{(\mu_p^{(i)} + \mu_n^{(i)})p^{(i)}}\frac{dp^{(i)}}{dx}\,, \tag{3}$$

where J is the electric current density calculated per QW. The boundary conditions for Eqs. (1) and (2) are: $p^{(p)} = p_0$, $n^{(p)} = 0$ as $x \to -\infty$; $n^{(n)} = n_0$, $p^{(n)} = 0$ as $x \to +\infty$. The fluxes of minority carriers at the junctions are determined by the diffusion processes: $j_n = -D_n^{(p)}\frac{dn^{(p)}}{dx}$ at $x = 0$ and $j_p = -D_p^{(n)}\frac{dp^{(n)}}{dx}$ at $x = w$. At the $p - i$ junction, the hole

concentration from the i side $[p^{(i)}(0)]$ and the electron concentration from the p side $[n^{(p)}(0)]$ are determined by the energy barrier Δ_p (of the $p-i$ junction) and the hole concentration p_0 in the p side of the structure:

$$p^{(i)}(0) = \frac{m_p k_B T}{\pi\hbar^2} ln\left[1 + e^{-\frac{\Delta_p}{k_B T}}\left(e^{\frac{\pi\hbar^2 p_0}{k_B T m_p}} - 1\right)\right] , \tag{4}$$

$$n^{(p)}(0) = \frac{m_n k_B T}{\pi\hbar^2} ln\left[1 + e^{-\frac{\Delta_p}{k_B T}}\left(e^{\frac{\pi\hbar^2 p^{(i)}(0)}{k_B T m_n}} - 1\right)\right] . \tag{5}$$

Here, $\hbar$ is the Planck constant, k_B is the Boltzmann constant, T is the temperature, m_n and m_p are the effective masses of electrons and holes, respectively. Similarly, at the $i-n$ junction the electron concentration from the i side $[n^{(i)}(w)]$ and the hole concentration from the n side $[p^{(n)}(w)]$ are determined by the energy barrier Δ_n (of the $i-n$ junction) and n_0. The voltage drop across the structure V can be found as

$$eV = E_G + E_{Fp} + E_{Fn} - \Delta_p - \Delta_n - e\int_0^w E dx\, , \tag{6}$$

where E_G is the energy spacing between the electron and hole subbands in the QWs, $E_{Fp} = k_B T\, ln\left[exp\left(\frac{\pi\hbar^2 p_0}{m_p k_B T}\right) - 1\right]$ is the Fermi level of the holes in the p side of the device, and E_{Fn} has the same meaning for the electrons in the n side and can be calculated similarly.

For numerical estimates, we assume the linear recombination mechanism with the recombination time τ_R different in the different device regions. As an example, let us consider a GaN/AlGaN LACE. We set $\tau_R^{(p)} = \tau_R^{(n)} = 0.1\, ns$, $\tau_R^{(i)} = 1\, ns$,[3] $m_n = 0.18\, m_0$, and $m_p = 0.8\, m_0$, where m_0 is the free electron mass. Then we assume that $\mu_n/\mu_p = 20$ and $\mu_n = 500\, cm^2/sV$,[14] and that D_n and D_p can be estimated using the Einstein relationship.[13] For $T = 80\, K$ this results in the ambipolar diffusion length $L^{(i)} = 1.2\, \mu m$, and diffusion lengths $L_n^{(p)} = 1.7\, \mu m$ and $L_p^{(n)} = 0.4\, \mu m$. The carrier concentrations p_0, n_0 are given in Table I. In Fig. 2(a) we present the distribution of the electrons and holes injected into the $p-i-n$ structure. The data are obtained for $w = 3.6\, \mu m$ and $J = 16\, mA/mm$. In the quasi-neutral region, the concentrations are nonmonotonic with a maximum p_M at the $n-i$ junction and a minimum p_m at the middle of this region. In the p and n regions, the minority carrier concentrations decay over the distances of about $L_n^{(p)}$ and $L_p^{(n)}$. The corresponding

energy diagram is shown in Fig. 2(b). The potential barriers at the junctions Δ_p and Δ_n are finite and decrease with increasing in current. For example, the $p-i$ junction barrier vanishes first at $J = 188\, mA/mm$. The built-in potential related to the diffusion field of Eq. (3) facilitates spreading of 'slow' holes through the extended i region. The total voltage drop across the $p-i-n$ structure with 5-nm QWs is $4.22\, V$.

Data collected in Table I for GaN and InN QWs allow one to conclude that under the planar double injection, high densities of electron-hole plasma - above $10^{12}\, cm^{-2}$ - can be achieved. For 5-nm QWs, the radiative recombination of the plasma will produce light emission centered at $344\, nm$ and $587\, nm$ for GaN and InN QWs, respectively; the wavelength can be scaled readily to the deep-ultraviolet range by using AlGaN or AlGaInN LACEs. Our calculations show that under lateral injection, the interband *population inversion* occurs across the entire i region for all cases presented in Table I. The population inversion can be reached at quite modest currents and biases. For instance, in a GaN-based LACE with ten QWs, a strip of area of $100 \times 3.6\, \mu m^2$ can be inverted in currents less than $16\, mA$ at $T = 80\, K$ [Fig. 2(b)].

In conclusion, contemporary group-III nitride technology allows fabrication of novel structures for light emitters - laterally, selectively doped QWs and SLs. In such sructures, planar $p-i-n$ regions with high concentrations of 2D electrons and holes are formed and highly-efficient double injection occurs when a bias is applied along the QWs. This results in high densities of 2D electron-hole plasma in an extended i region and population inversion of the conduction and valence bands. We suggest that planar double injection that occurs in LACEs is an efficient method for electrical pumping of short-wavelength nitride-based lasers.

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Table I. Parameters characterizing the lateral double injection in the nitride-based $p{-}i{-}n$ structures with (a) $p_0 = n_0/2 = 5 \times 10^{12}\,cm^{-2}$ and (b) $p_0 = n_0 = 10^{13}\,cm^{-2}$. U/e is the applied voltage.

QW	T	J	Δ_p	Δ_n	U	p_m	p_M
Material	K	mA/mm		meV		10^{12}	cm^{-2}
GaN							
(a)	80	16	11	92	66.6	0.9	2.3
(b)	250	80	20	42	284	2	6
InN							
(a)	80	37	12	153	74	1	2.9
(b)	300	110	27	73	285	2.4	6.6

FIGURES

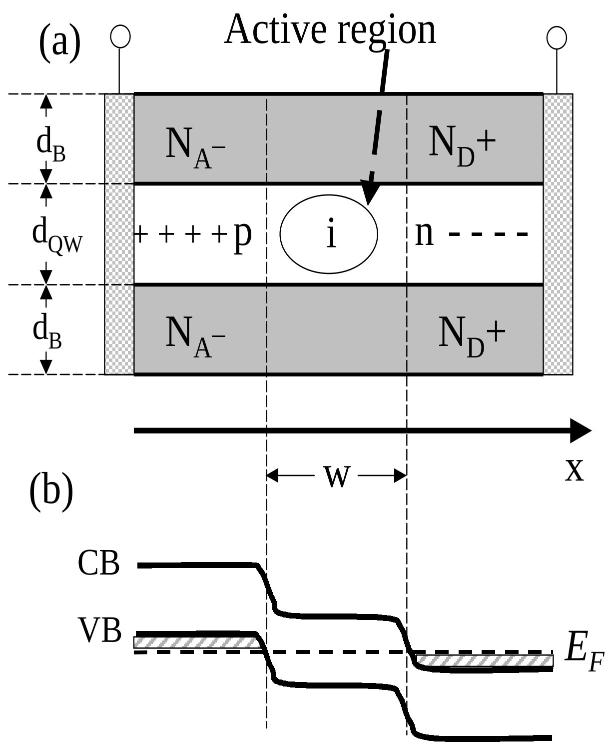

FIG. 1. Schematic illustration of (a) the proposed multi-layered lateral $p-i-n$ structure and (b) energy band diagram in the lateral direction with no bias. CB and VB indicate the lowest populated energy levels in conduction and valence bands, respectively.

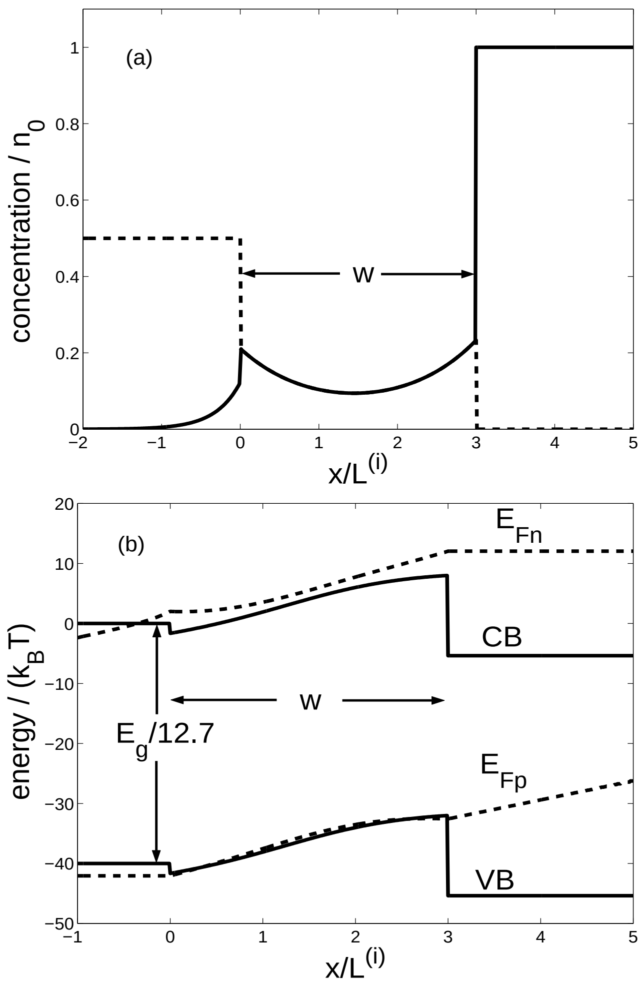

FIG. 2. Characteristics of the proposed lateral $p-i-n$ structure with GaN QWs at $T = 80K$ in the double injection regime: (a) Concentration of the injected electrons and holes (in the unit of n_0) versus distance x along the structure (in the unit of $L^{(i)}$ which is the diffusion length in the i region). The electron (hole) density is represented by the solid (dashed) line. (b) Energy band diagram of the structure. The energies are given in the unit of $k_BT = 6.9\,meV$. The depletion layer thickness is neglected as discussed in the text. The operating parameters are given in Table I [GaN (a)]. CB and VB indicate the lowest populated energy levels in conduction and valence bands, respectively.